A SURVEY OF VISUALIZATION IN INDUSTRY

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Abstract

This paper investigates how a variety of industries and application areas visualize large quantities of data in real-time. This research stems from the AVATAR project's desire to understand data visualization better by gaining insight from other areas of industry and stimulating further creative thought. The AVATAR project (Advanced Visual Tools and Architectures), funded by the Advanced Architectures and Automation Branch (Code 588) of NASA's Goddard Space Flight Center, specializes in data visualization and lately has focused on visualization of constellations of satellites. This paper represents the first installment of research of this topic. A new installment is planned each of the next two years to keep track of the latest developments in data visualization and real-time monitoring.
Keywords: data visualization, NASA: GSFC, real-time monitoring, satellite constellation

Motivation

The efficient, informative display of real-time telemetry from spacecraft is fundamental to NASA Goddard Space Flight Center operations. While NASA has a wealth of experience in mission control systems development, the movement toward developing constellations of spacecraft raises new issues in data visualization and real-time mission monitoring. In this study, we research other areas of government and industry that attempt to address the same basic challenge as satellite constellation and multi-mission management, namely, to develop effective solutions for the "real-time monitoring of lots of little things."

Organization

This paper is organized into six sections:

- *Motivation* (this section) which also describes the organization of the paper;
- *Case Studies*, which describes each product or industry, with an eye toward certain key questions and issues;
- *Analysis*, which breaks down each case study into five analytical elements, and more closely ties the research findings to the AVATAR project;
- *Conclusions*; which summarizes the most interesting ideas and important lessons learned;
- *Further Directions*, which outlines some possible areas for future investigation; and
- *Bibliography and Acknowledgements*, where we thank the numerous individuals who helped us with our research.

Case Studies

In this section, we present the body of our research. With each contact or product, we have focused our investigation on the following issues and questions:

- Who the team is and what problems they address;
- What tools they use for real-time monitoring of their system;
- What are the relevant error conditions and alarms and how are they signaled to the user or operator;
- What kind of executive summary views they have, and is there a notion of drill-down;
- How they use color and sound in their interface; and
- Can they operate in a "lights-out" environment, if applicable.

In some cases, we've added our own observations of the notable aspects of a particular industry's visualization or monitoring approach. The *Analysis* section expands on these observations and relates it to current AVATAR constellation software.

The following lists each case study discussed in this section:

- Montgomery County Traffic Operations
- Air Traffic Control
- Washington, DC Metrorail
- Network Monitoring
- Performance Analysis of Complex Machinery
- HighTower Software's TowerView
- Visualizing Financial Data with Heatmaps
- Coors Brewing Company
- United Parcel Service
- Honda of America

Montgomery County Traffic Operations

The densely populated Washington, DC suburb of Montgomery County, Maryland, is faced with predictions of 70% growth in vehicle traffic with only 20% growth in roads. This, of course, is in addition to the large amount of traffic they have today. Part of the solution is to make more efficient use of roadways, which is where their impressive Transportation Management Center comes in.

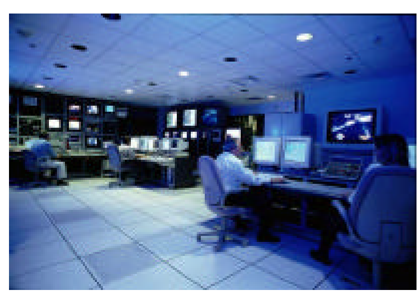

Figure 1: Transportation Management Center

The center monitors the county from a control room in downtown

Rockville. From the room, the four-person team uses roughly 30 computer and television screens and various software systems to keep an eye on 750 intersections, 250 city buses, and over 100 live traffic cameras. With these systems, traffic light timing can be changed on-the-fly, getting a behind-schedule bus, for example, back on track with a healthy dose of green lights. By touring this facility and listening to manager and visionary Emil J. Wolanin, we learned not just about the systems and techniques, but also lessons-learned in the world of monitoring software.

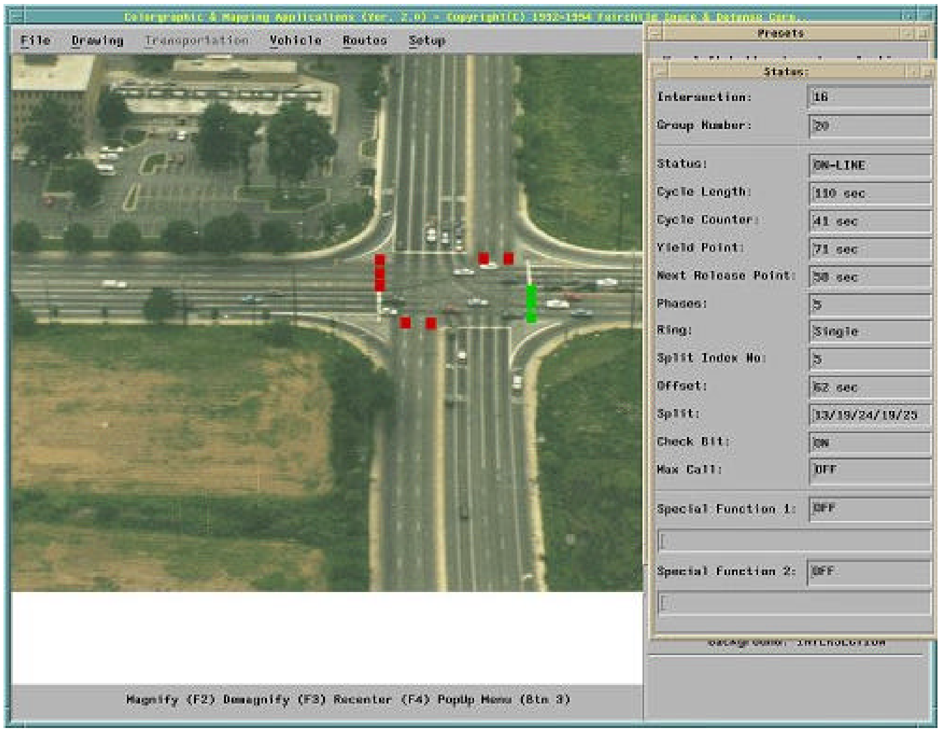

Figure 2: ATMS Intersection Status

For the past decade, the center has been using a UNIX-based Automated Traffic Management System or "ATMS[1]". The system starts with scanned images of street maps[2] commonly used by fire, ambulance, and other agencies, as well as still photos of roadway. Using live data gathered from traffic lights and magnetic "loops" buried in the pavement at each intersection, ATMS overlays graphics on top of the map image to show traffic volume and signal status (see Figure 3). By configuring ATMS with expected number of vehicles based on time of day, portions of the road are highlighted in green or blue to show normal or out-of-range flow.

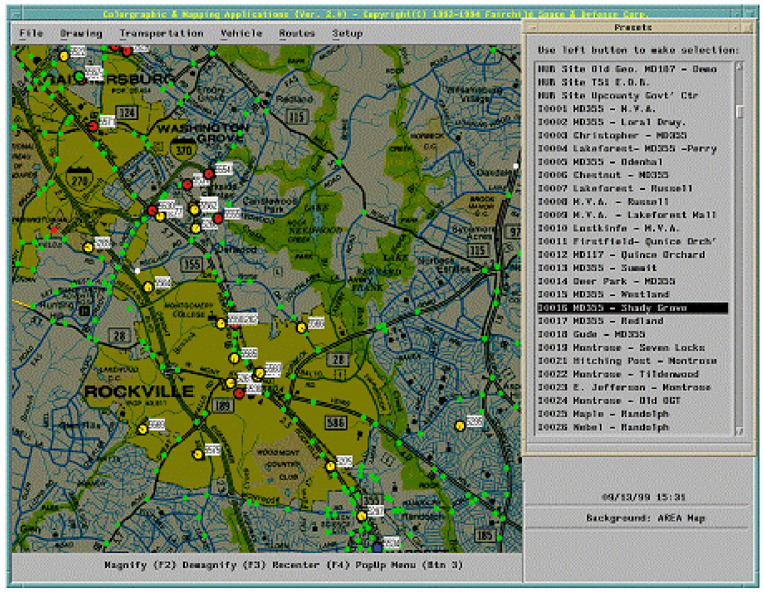

Figure 3: ATMS Signal and Traffic Volume Status

In addition to the graphical display, an event log shows further detail (see Figure 4). "Seasoned" members of the traffic team often jump right to the log, deciphering equipment codes that indicate problems such as outages caused by lightning strikes.

Despite the power of the ATMS system, it actually goes largely unused. While the ideas behind its design were sound, three fundamental limitations have kept it from being a key part of the team's toolset. First, there has been a high cost and large time commitment to keep map images current. Second, it takes a long time to configure the expected traffic volumes "just right" so the colored

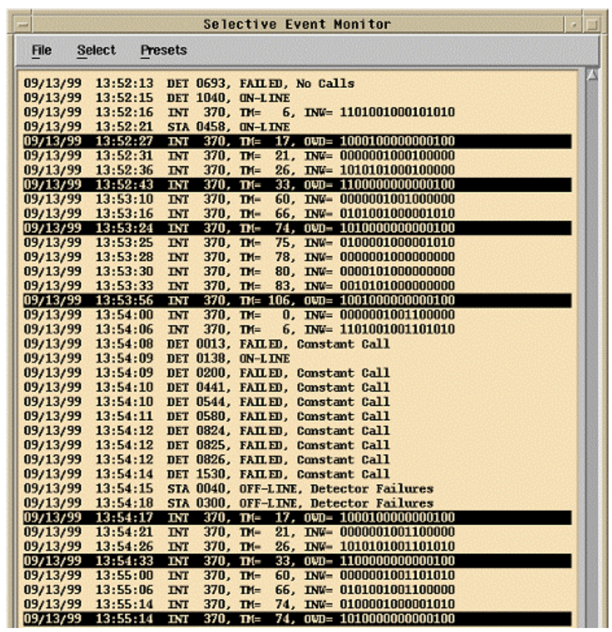

Figure 4: ATMS Event Monitor

[1] For an amazingly comprehensive website on the ATMS software, see http://www.dpwt.com/kiosk/atms/ .

[2] These are the ADC street maps available to the public at local stores.

displays give worthwhile information. Lastly, and probably most significantly, is the fact that ATMS is not integrated with all of the other systems that the center uses. This means the operator has to move from system to system, best described by Mr. Wolanin as "that's why our guys have wheels on their chairs". If the system isn't in front of them and isn't terribly useful, it won't get used.

The future, however, is much brighter. Montgomery County is working with a vendor on a new ATMS system that will run on the Microsoft Windows operating system (see Figure 5). The key feature of "ATMS2" is its ability to bring disparate systems into one desktop[3]. Maps, traffic flow, signal status, construction, traffic cameras, city buses, and other elements will be monitored and controlled from a single workstation. Details can be hidden for simplicity. When a traffic accident causes congestion, for example, ATMS2 will present the operator with past solutions, such as changing the timing of all lights within a mile of the incident. ATMS2 will also help plan the routes of service technicians sent out to fix traffic equipment.

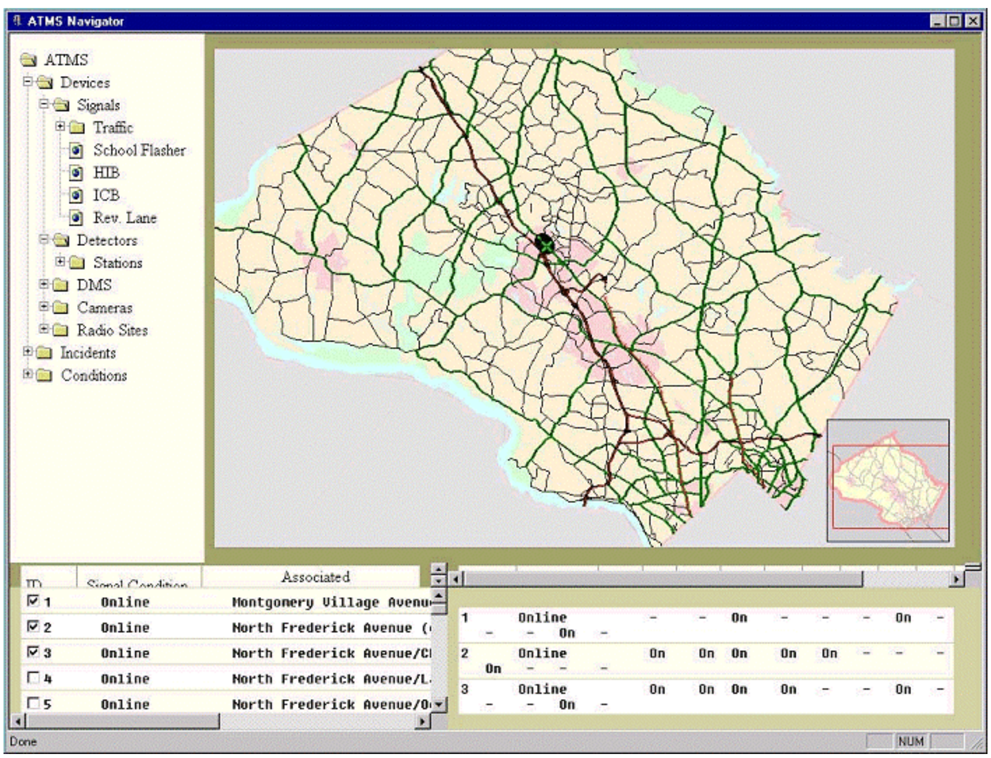

Figure 5: Prototype of the New ATMS System

While all this new technology is great, the center's strategy assumes that new systems won't last much beyond 5 to 7 years, and therefore doesn't take big risks with "too new" unreliable technologies. Furthermore, traffic management systems will become, in the long term, more predictive than they are today, allowing the team to solve problems before they become too large.

[3] To maximize display, the ATMS2 system uses two monitors side-by-side that together act as a single desktop.

A great “lesson learned” the center: “don’t automate before you understand what you’re doing”. In other words, a team is less likely to trust the output of a tool they’ve configured if they don’t have a firm grasp on what it takes to do so by hand.

Air Traffic Control

Air traffic control and satellite constellation mission management seem to present some of the same technical challenges. Both are concerned with the safety of objects flying miles above the Earth's surface. Both produce large amounts of data that must be presented to and understood by its personnel. Both increasingly rely on computerization and automation to reduce cost and improve safety. With these similarities, it behooves us to take a look at the systems in use by the air traffic control industry.

Air Route Traffic Control Centers (ARTCC) provide air traffic control for aircraft outside airport jurisdiction, which generally extends 30 to 40 miles around an airport. Everywhere outside of that space– which is most of the country– falls within the jurisdiction of an ARTCC. There are 20 ARTCC regions in the United States, each of which covers and area of hundreds of square miles. This region is further subdivided into sectors of approximately 80 square miles. Each sector is under the control of one air traffic controller and typically contains 15 to 30 aircraft at a time.

The Traffic Management System is comprised of the equipment, persons, and procedures that keep the U.S. air traffic system operating. This system incorporates all aspects of ensuring that air traffic remains safe, orderly, and efficient. It incorporates the ARTCC, the airports, and the airlines.

The Enhanced Traffic Management System (ETMS) is a program that is concerned with modernizing air traffic equipment and software. The ETMS relies on sophisticated radar data processing as well as databases of flight planning information. Air traffic controllers then have access to all of this data to help them perform their jobs. Our research focuses on the ETMS displays.

Traffic Situation Display

The Traffic Situation Display, or TSD (Figure 6), is the primary display that an ARTCC controller uses. This display is a modern update of the old radar screen displays that air traffic controllers used to use. The TSD plots the location of the aircraft over a geographical map, and can also display information about each aircraft at the controller's discretion. To plot all of this information, the TSD draws on the FAA's radar data processing infrastructure. Every in-flight aircraft in the U.S. can be displayed at once, or the view can be zoomed and filtered to isolate a particular geographic region.

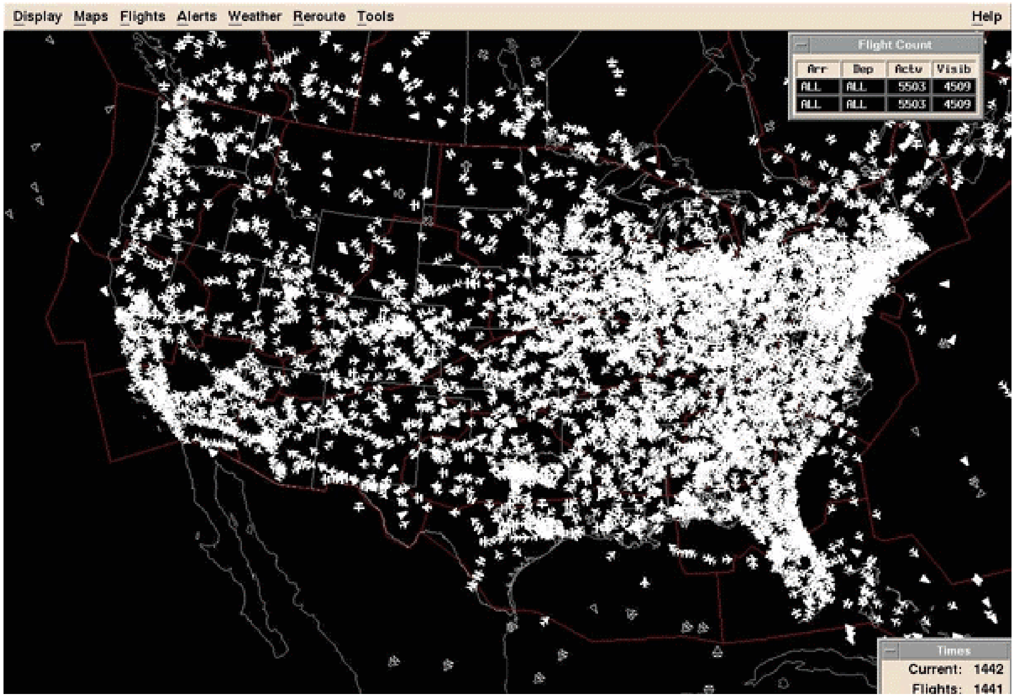

Figure 6: The Traffic Situation Display (TSD)

The "background" of the TSD shows regional features: the borders between states, the regions belonging to each ARTCC, the sections belonging to each controller, the locations of airports, and local high-altitude terrain. The aircraft are plotted over this backdrop in proper relation to all of these features. Each aircraft is plotted as a target and data block: the target is an icon showing the heading of the aircraft, and the data block can be configured to display information about each aircraft such as its designation, altitude, velocity, and heading. More information about the aircraft– such as its origin, destination, and flight plan– is available from a separate screen.

Controllers can zoom and filter the TSD to the section of airspace for which they're responsible. Not only can they filter out the aircraft that are outside of their region laterally, but also those that are above or below their region. ARTCC controllers generally deal with aircraft that have an altitude between 18,000 and 60,000 feet. This space of 42,000 vertical feet is often divided into two separate sectors– one above the other– that are administered by separate air traffic controllers.

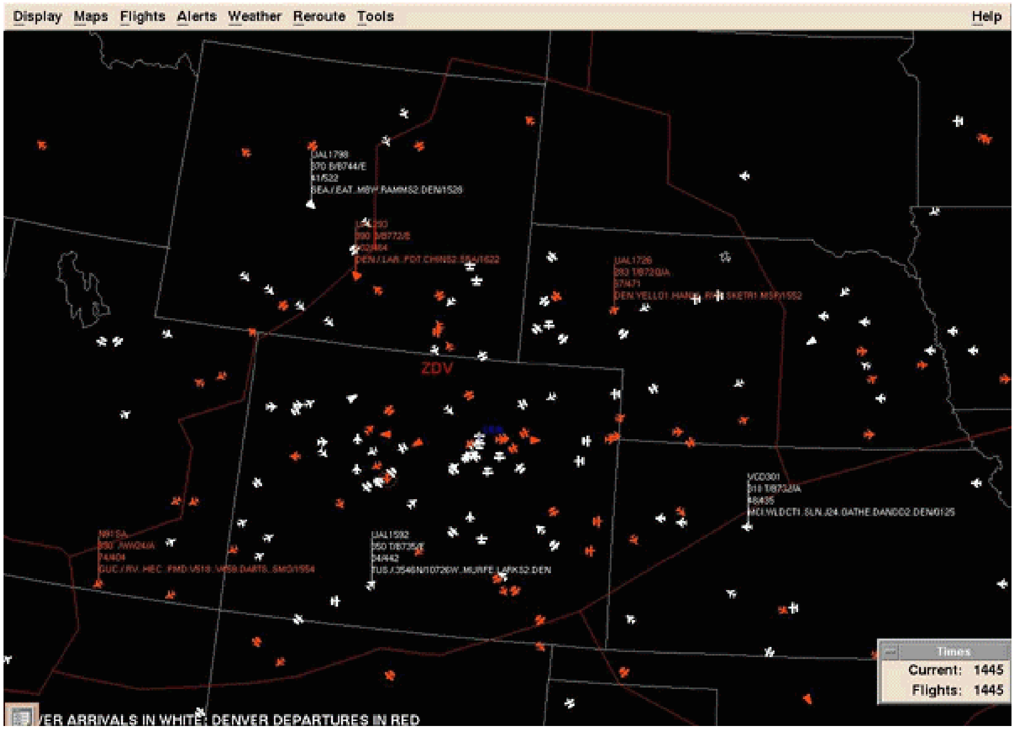

Figure 7: Color -coding the TSD

Filters can be used to keep superfluous aircraft from cluttering the view, and can be applied to visible aircraft to highlight certain characteristics. For instance, a controller can color-code the aircraft in his region to indicate whether they are inbound to or outbound from a local airport, whether they are climbing or descending, or whether they are moving faster than a certain speed.

Monitor Alert

Monitor Alert is a process that calculates air traffic congestion around airports and flight paths up to four hours in advance of the actual event.

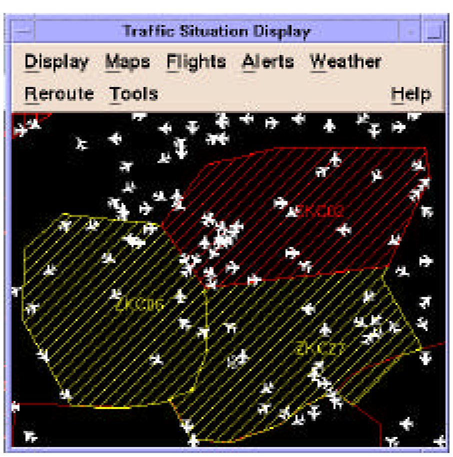

Figure 8: Monitor Alert in the TSD

Using data from aircraft en route, flight plans filed by the airlines, and known airport runway capacities, Monitor Alert can determine if the volume of air traffic will exceed the capacity of any region. If so, the region will be highlighted on the appropriate controller's TSD.

The alert appears on the TSD as a shaded area: red for an active alert, yellow for a projected alert, and green for an addressed alert. Drilling into the alert on the screen, the controller is presented with a bar chart showing the number of aircraft the sector can handle (green), the number of aircraft in the active alert (red), and the proposed number of aircraft once the alert has been addressed (yellow). The bar chart shows these three values in 15-minute increments for the duration of the alert. The controller can then display all of the flights (real and projected) affected by the alert so that he or she can visualize the spacing and routes involved in creating the demand. This information helps the controller decide how to alleviate the problem.

Other ETMS Features

Conflict Alert is an automated process that alerts controllers to impending infractions of aircraft separation limits. When it appears that the headings of two aircraft will bring them dangerously close to each other, Conflict Alert highlights the aircraft on the TSD.

The En Route Minimum Safe Altitude Warning (EMSAW) alerts controllers when an aircraft has entered a region where its altitude is too low to clear the terrain.

Washington, DC Metrorail

The Washington Metropolitan Area Transit Authority (WMATA) operates 120 trains at 83 stations across a 1,500 square mile area of the region, totaling over 103 miles of track carrying almost 600,000 passengers per weekday. At the Operations Control Center (OCC) in downtown Washington, DC, operators monitor real-time telemetry sent from each passenger station to relay status information about a variety of sources, including:

- the electrical system (transformers, breakers, etc);
- numerous fire and intrusion alarms and alerts at each station;
- approximately 3,000 track circuits[4];
- approximately 600 track switches that determine train direction;
- passenger fare gates at each of the 83 stations;
- status of 180 elevators and 557 escalators system-wide; and
- the location of the trains themselves.

WMATA personnel utilize ROCS, the Rail Operations Computer System, for real-time monitoring of the system. Unfortunately, screenshots were not available for use in this paper. The OCC houses approximately 125 CRTs which display any of the over 3,000 screens in the ROCS software. ROCS is accessed by– and maintains access permissions for– eight categories of users, ranging from engineers, to transit police personnel, to line control supervisors and superintendents who perform the day-to-day

[4] The Automatic Train Control system is composed of contiguous track circuits ranging from 50 to 1,500 feet in length.

operations of the metro lines themselves[5]. A five projector multi-screen display on the front wall projects the full system map by Metro line. The display updates in real-time with train identification, location, and many other status indicators. Three long rows of consoles with CRT monitors dominate the room, organized by Metro line. Line control supervisors staff these displays to manage the second-by-second transportation system operation and investigate problems or enact procedural control maneuvers. The maintenance operations center adjacent to the OCC maintains contact with WMATA supervisors and maintenance personnel at the site of a problem, serving as the eyes and ears of maintenance workers as well as a point of contact for new problem reports from train operators or other WMATA personnel.

After login to ROCS, a user selects a line to monitor (Red, Green/Yellow, or Orange/Blue), resulting in a line display screen that graphically depicts the contour of the selected line and the position of each station. This screen leads to an overview screen of a station or a pre-configured range of neighboring stations within the line. The overview screen shows tracks, signals, track circuits, position of trains, and location of stations and interlockings (areas where trains can be diverted to the opposite rail[6]). A further mouse-click yields a detailed view that shows interlockings, fans, pumps, electrical system elements, intrusions, and platform details. A right-click posts a menu which leads to additional information, including:

- station schematics, which depict station-level elements, such as staircases, electrical systems, intrusions, trains at the station, and much more;
- electrical system view, which graphically illustrates every transformer, transducer, and power source within a region;
- surface area maps, scale drawings of the area surrounding a metro station; and
- additional pre-defined information such as train schedules, computer system configuration, diagnostics, reports, and more.

An impressive number of these screens update in real-time based on telemetry from myriad data sources. Other low-level data consists of static, character-based labels and indicators of data points relevant to the selected station, train, interlocking, or other system element. Overall, though, it seemed as if one could double-click on every symbol in the overview and detailed view to access further levels of detail.

The system communicates alarm conditions, detected by the software or train operators, in several different ways:

- train operators report problems with the train itself by radio to the communications center;

[5] Line control supervisors are what we would call "operators". An example of such an operation occurred during our visit, as line control supervisors redirected one train from the inbound rail to the outbound rail as evening rush hour began.

[6] Obstructions on the track or reassignment of a train during rush hour may necessitate such redirection.

- train control equipment failures are detected by the software or reported by train operators using the service;
- major and minor alarm lists communicate alerts such as intrusion and fire alarms;
- overview and detail screens signal alarm status of displayed devices by flashing device icons in different colors;
- a message area which cannot be disabled always shows the three most recent alarms; and
- audio annunciators connected to workstation keyboards emit alert tones to call attention to major alarm conditions (e.g., fire, blown fuses).

While OCC staff perform a variety of roles, all are proficient in using the ROCS software, and together form a team who as a whole is extremely effective at operating the Washington, DC metro, a complex system of mechanical, electrical, and civil engineering. The software suits their needs very well, providing real-time access to large amounts of multivariate data and presenting them in an intuitive, point-and-click display for 15,000 control items and 25,000 status items.

Network Monitoring

Administrators of large computer networks utilize sophisticated tools to monitor and troubleshoot the numerous elements that comprise their network. Central to these tools is the visualization of complex phenomena within a network, including both structural and statistical elements, while simultaneously alerting administrators to error conditions. A good network monitoring tool should enable administrators to command or reconfigure devices remotely, as well as support a comprehensive set of real-time features, including:

- automatically detecting structural modifications to the network;
- detecting performance bottlenecks;
- recognizing hardware failures;
- notifying administrators of problems via pager or an email;

Recent enhancements imbue network management software with some limited amount of intelligence to perform preliminary analysis of symptoms. This eliminates redundant information– such as a storm of events that all point to the same problem– allowing administrators to focus on the core of a problem. It also fosters automation of repetitive tasks: administrators can configure the software to perform certain routine tasks automatically in response to common troubleshooting scenarios, such as installing a software patch when it becomes available.

Network administration tools typically present visual information in any of three ways: topographical network maps organized geographically or based on business distribution; tree-like hierarchical views; and time-stamped, color-coded network event logs.

There are numerous network management vendors, some of who offer robust products suitable for managing complex systems. Principal network vendors include Hewlett-Packard, IBM, Computer Associates, BMC, OSI, and Ipswitch.

Network Node Manager (NNM)

Hewlett-Packard's Network Node Manager offers the following main benefits:

- displays current status and measure current performance of the network;
- analyzes past performance and subsequently predicts potential issues;
- automatically discovers computers as they are added to the network; and
- can be programmed to respond automatically to predefined events.

Users design maps in NNM to convey network topology. Symbols represent each element (node) and depict physical connections, while red-yellow-green color changes and status icons on each symbol impart additional information (see Figure 9). Users can develop multiple maps and submaps and arrange them hierarchically, supporting the familiar paradigm of overview with drill-down.

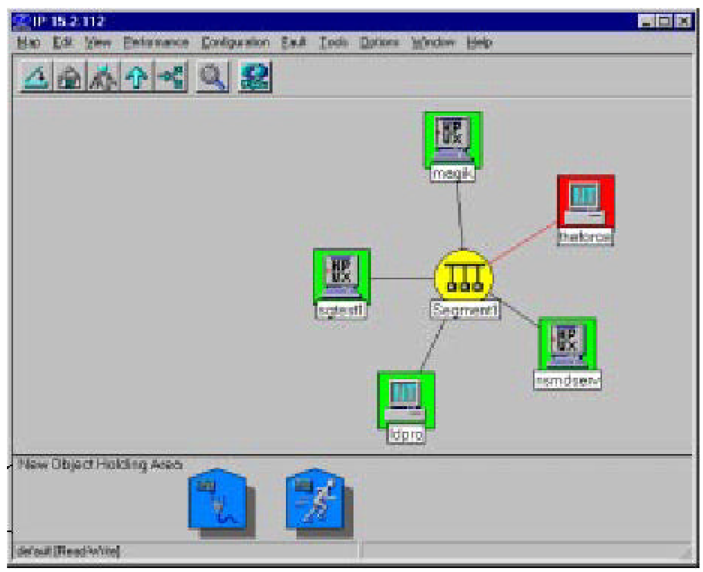

Figure 9: Use of colors to represent status of nodes in a map

The NNM Alarm Browser (Figure 10) logs many different categories of alarms[7] triggered by background polling or specialized agents that detect anomalous conditions. Users determine which network events trigger an alarm, and configure priorities, colors, and groupings for all alarm types. The Alarm Browser supports a variety of sort, filter, and search operations, as well as automatic identification of errors when a pre-configured sequence of events occurs.

[7] Alarm categories include Error, Threshold, Status, Configuration, and Application Alert Alarms.

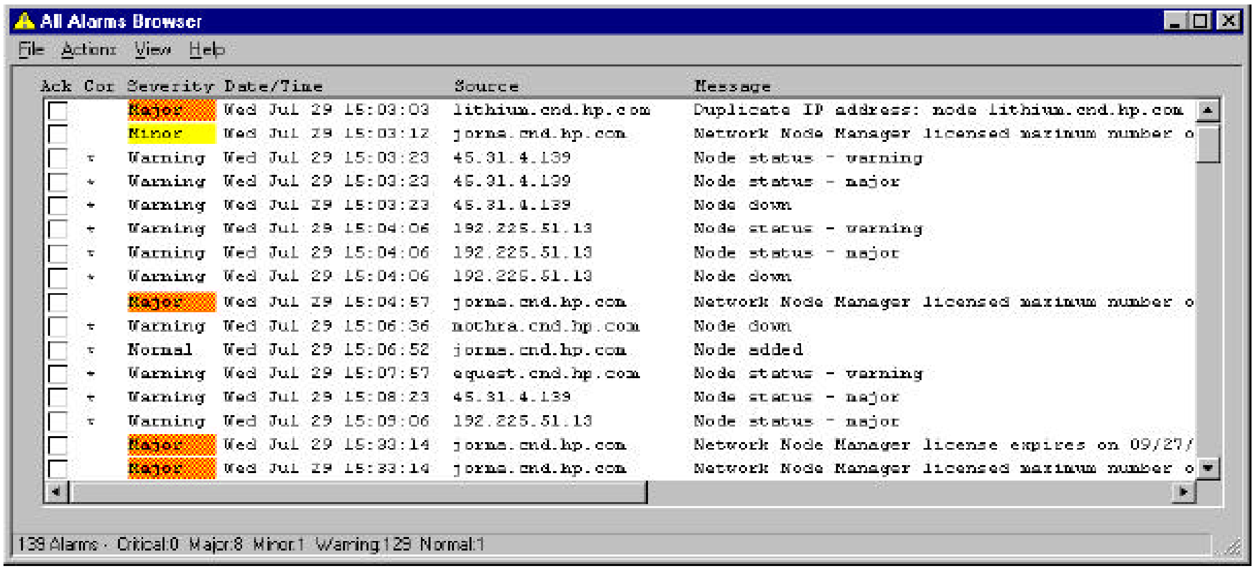

Figure 10: All Alarms Browser window

Thresholds play a key role in triggering events and determining the color of a symbol. NNM generates a threshold event as a result of a limit violation, and a rearm event once the parameter returns to an acceptable range (see Figure 11). Moreover, NNM users can derive health status from several nodes when they apply expressions (mathematical formulae) on a group of values from related nodes.

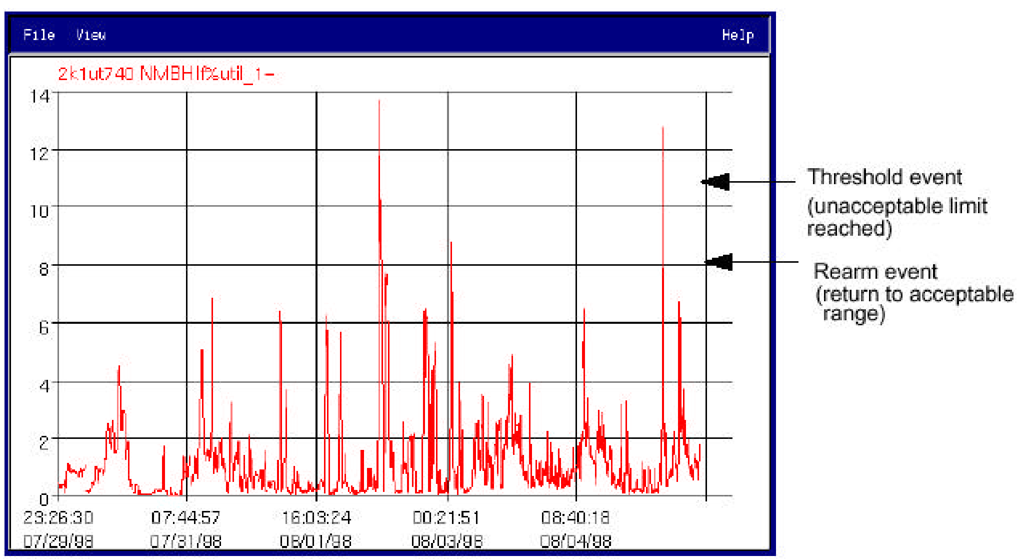

Figure 11: Illustration of threshold and rearm event triggering on a strip chart

Finally, NNM can be configured to take automatic corrective action when a predefined event occurs, including notification via pager or email should the problem require administrator intervention.

Tivoli

IBM sells a suite of tools called Tivoli for networking management. Tivoli bears many similarities to Hewlett-Packard's Network Node Manager, but does possess some distinctive elements outlined below.

While HP's NNM features network maps and event logs, Tivoli presents the network in a hierarchical tree view (Figure 12). Properties of the selected node appear in the adjacent pane (although largely obscured in the figure). Unlike map views, tree views confer the ability to examine several levels of hierarchy simultaneously by expanding any given branch to the desired level, while hiding details of unwanted branches.

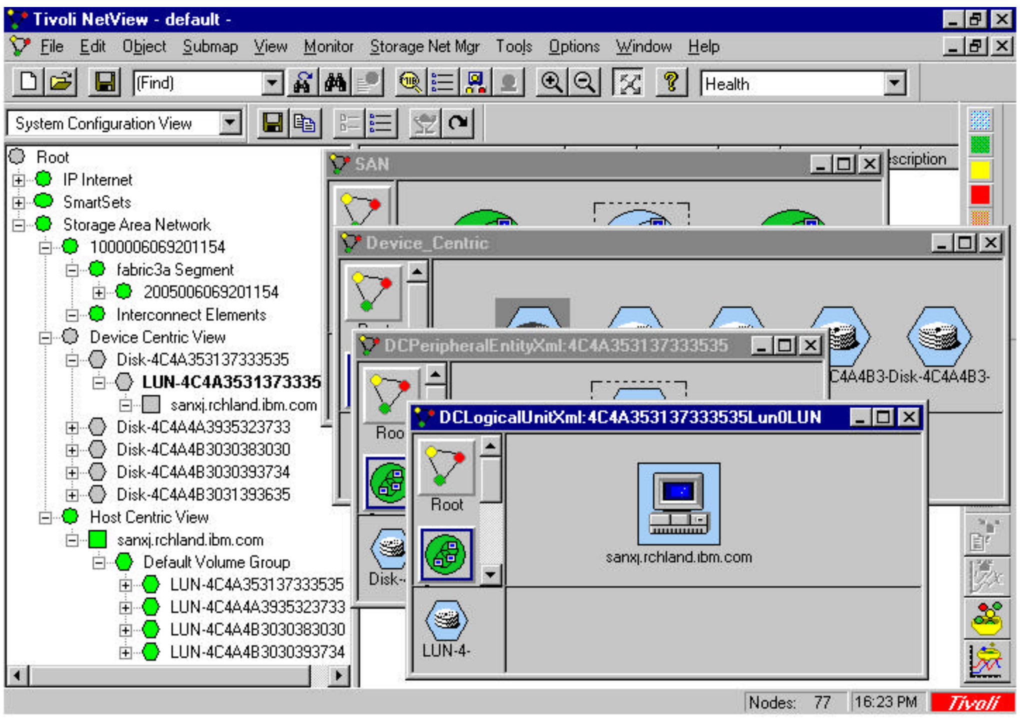

Figure 12: Example of the tree structure and drill-down via cascading windows

In addition, double-clicking a tree node brings up detail windows with icons and controls specific to the selected network element. Successive mouse clicks bring up additional windows with images for lower-level elements. The combo box (labeled "System Configuration View" in the figure) suggests that multiple views can be defined, each with a different hierarchical structure.

Tivoli presents an interesting alternate approach to drill-down. Figure 13 illustrates drill-down in a pie chart by means of a scrollable legend that "floats" above the other windows. When the user double-clicks on a colored button in the legend, the chart and legend update with the elements in the next level in the hierarchy.

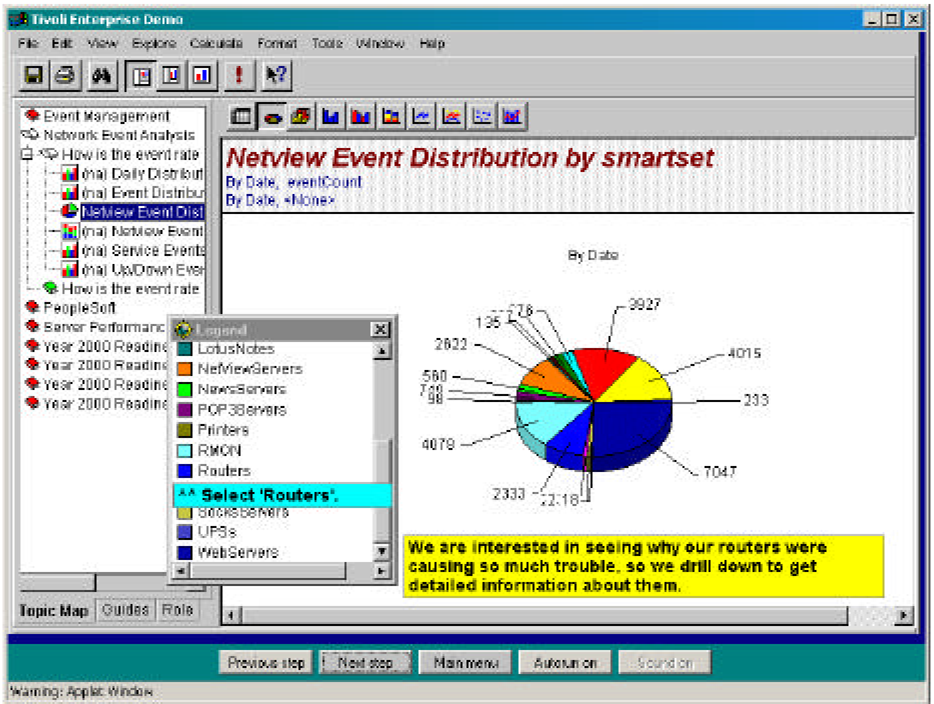

Figure 13: Interactive legend facilitates drill-down in a chart

Performance Analysis of Complex Machinery

To optimize the performance of multiprocessor systems, computer designers require powerful profiling tools. Not only must these programs gather vast amounts of data coming at high speed, but they also must present thousands of points of data in a compact form. Once the data are plotted, the crucial information lies in the resultant visual patterns and point density. The Rivet Project at the Stanford University computer science department addresses these issues of visualizing complex systems.

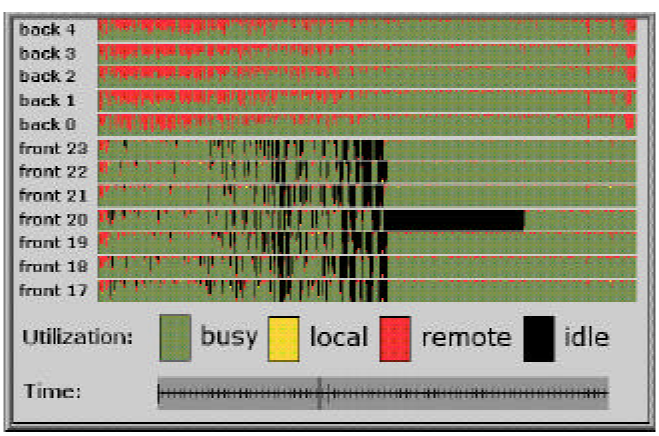

Figure 14: Charts which conveys information in the form of patterns

Figure 14 shows a Rivet screen concerned with the analysis and visualization of parallel application memory usage[8]. While no one point, row, or time slice is itself significant, the overall activity patterns are clearly evident. The color-coded legend at the bottom further characterizes the data and

[8] The subject here is the Argus parallel rendering library. Figure 14 is only a portion of the full screen-shot; see http://www-graphics.stanford.edu/projects/rivet/#argus for a full account of this research.

draws the eye to clusters of like activity.

Figure 15 is even more compelling. Here we see a "pipeline utilization" visualization for analysis of superscalar processor performance[9]. Processor designers can identify regions of poor instruction throughput from this visualization. Multiple time scales displayed simultaneously allow users to focus on areas of interest while maintaining overall context. As indicated by the scale for each row listed in the margins and by the blue shading between rows, the bottom row provides an overview (1 to 1 million), while the next row zooms in on the range selected by the yellow manipulator (100K to 150K), and the next row shows the most detailed view (120K to 122K). The histogram corresponds to the most detailed row.

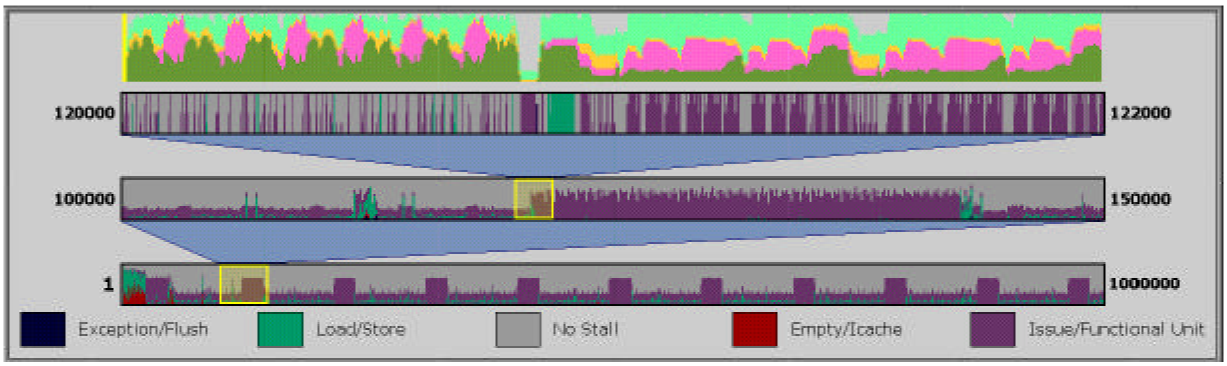

Figure 15: Illustration of (a) use of color and (b) innovative drill down

HighTower Software's TowerView

In the mid-1990s, JPL developed the MSAS Data Monitor as a generic tool for graphical monitoring and analysis of large amounts of real-time data. In 1997, the technology was transferred to industry as the chief developer started a company based on this product. The result is HighTower Software's TowerView package, "a visual data discovery solution for environments with massive quantities of rapidly changing, business-critical data." TowerView, like MSAS before it, is a generic product customizable to a wide range of applications (e.g., network management, pharmaceuticals, financial data, and of course satellite operations). The basic premise at HighTower is that "traditional monitoring tools [...] do not scale sufficiently well to accommodate increasingly large amounts of data." Applying hierarchy to the data is considered a "work-around solution", because they "never actually solved the problem of data overload, they merely created a scheme for imposing order on the problem." As a result, TowerView employs the technique of *visual data monitoring* to display over 100,000 points in a single display, called the CyberGrid (see Figure 16).

[9] This figure shows only a portion of multiple integrated screens. See http://www-graphics.stanford.edu/projects/rivet/#pipeline.

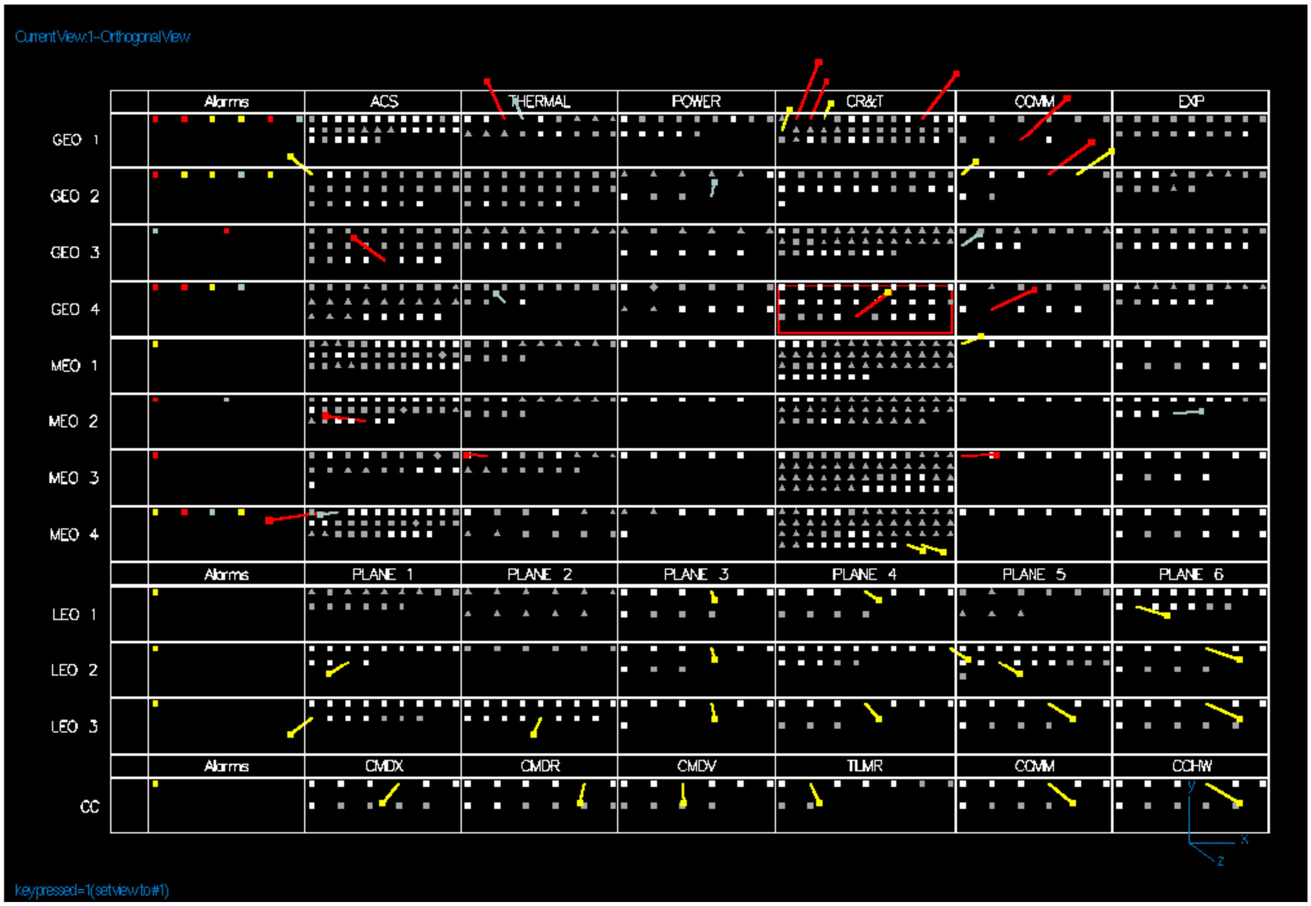

Figure 16: TowerView CyberGrid

With CyberGrid, engineers organize the data according to operational need. Multiple configurations can be created in a very short amount of time to support different views brought about by changing requirements. In a hierarchical representation, when an alarm fires, operators must "traverse each branch of the pre-configured hierarchy to determine where attention is required." In CyberGrid's executive summary, when a mnemonic reaches an alarm condition[10], its graphical shape (square, circle, or triangle, depending on the type of parameter) rises on a "tower" above the grid proportional to the severity of the alarm, changing color as it reaches certain severity thresholds.

The entire CyberGrid supports full three-dimensional movement (x-, y-, and z translation as well as roll/pitch/yaw orientation) with savable viewpoints. By clicking on the tower, operators can view mnemonic details (Figure 17).

[10] The CyberGrid supports limit alarms, trend alarms, and count alarms, plus the ability to set an alarm for a derived mnemonic.

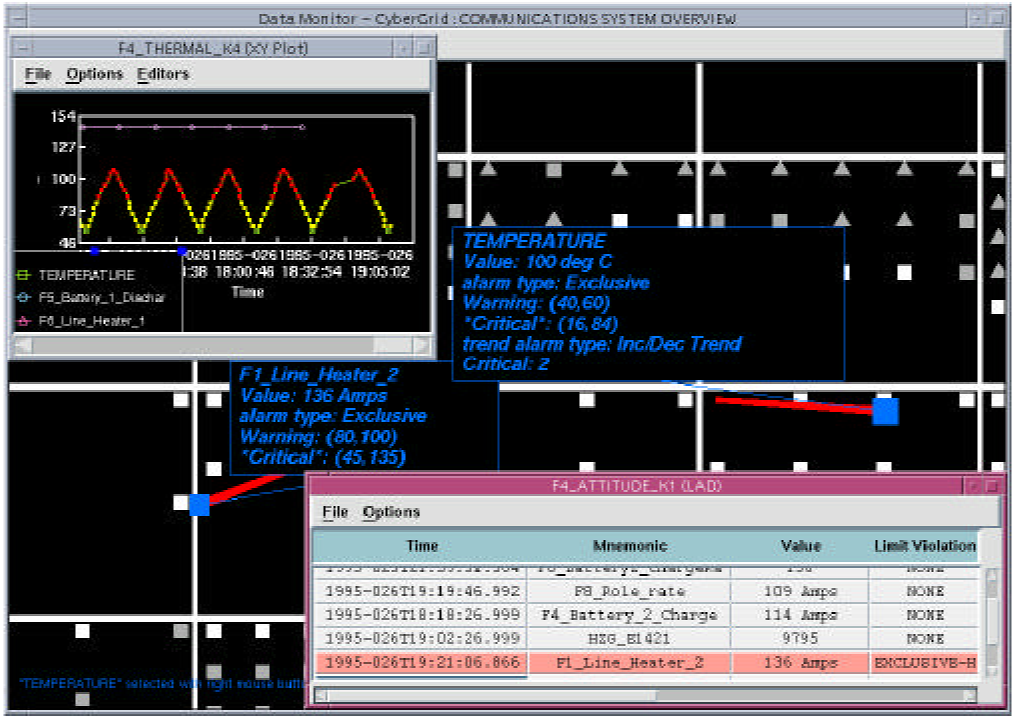

Figure 17: CyberGrid with details accessed from a single mouse click

Visualizing Financial Data with Heatmaps

In the financial world, information overload is a serious problem and is on the rise. Financial market professionals have increasing numbers of stocks to chart, clients to serve, and news to review. NeoVision specializes in visualization of financial data, featuring three main product offerings:

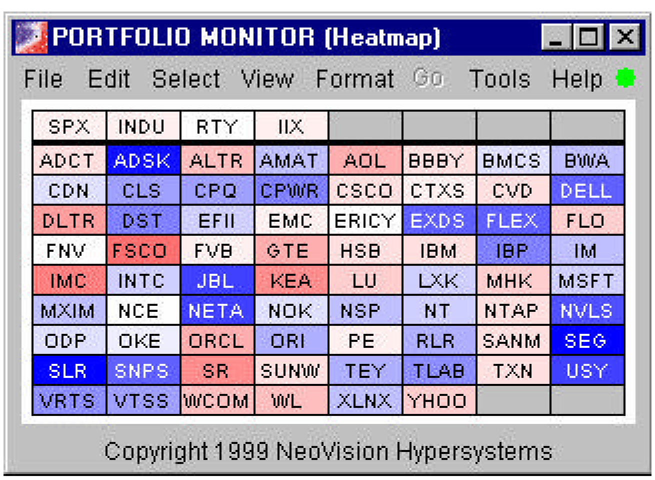

Figure 18: Heatmap "executive summary"

- Heatmaps, which organize financial data in a grid of color-coded squares (see Figure 18);
- WebHeatmaps, which extend Heatmaps and deploy them on the Internet; and
- RiskMaps (not pictured), which overlay a hierarchy over Risk systems and data warehouses.

Heatmaps accept live data and calculate in real-time what is "*Hot*" and "*cold*", and display their results in a red-blue color gradient. Users right-click on a square to bring up details (see Figure 19). WebHeatmaps (Figure 20) bring this technology to the Internet and can function as a snapshot, in which web pages are updated with each reloading, or as a dynamic Java applet that updates in real-time. Snapshot WebHeatmaps are server-side components that output HTML and DHTML, and support ASP (and soon JSP) control.

Figure 19: Heatmap with drill-down

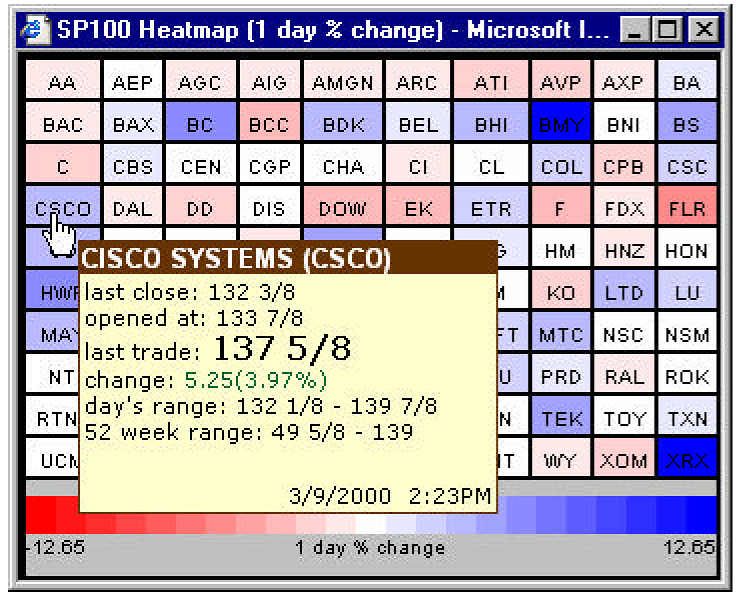

Figure 20: Stock-tracking WebHeatmap with drill-down

Coors Brewing Company

Coors Brewing Company is the third-largest brewing company in the United States, selling over 700 million gallons of beer in year 2000. They monitor an estimated 30,000 data points firing from once per second to once per 10 minutes- most at least once every three seconds. Mr. Joe Hageman, Manager of the Quality and Productivity Initiative, likened their collection of real-time data to that of a flight recorder. Real-time control system GUIs graphically depict tank fill levels, valve status, alarm status, and other indicators relevant to the brewing and packaging processes. Unfortunately, screenshots were unavailable. While nothing extraordinary stood out about their real-time procedures and data visualizations, it was interesting to hear that three years' worth of data is archived for trending analysis, compressed, and stored in specialized databases. Overall, there were actually a surprising number of similarities between real-time monitoring of beer packaging and satellite engineering data.

United Parcel Service

United Parcel Service delivers approximately 13 million packages each day, employing an extensive network of distribution centers, vehicles, and personnel to keep things on time. Making efficient use of these resources means saving money, but doing so requires analyzing vast quantities of data. To this end, UPS's Strategic Process Management Group investigated MUSE, the "perceptual computing" product from MUSE Technologies.

Although UPS didn't go beyond the prototype stage with MUSE, they learned a few things along the way. The three strengths of MUSE, in UPS' view, include the ability to "fly" through the data in a virtual craft, the ability to handle multiple data sources, and that it is supported by a company with consulting expertise in a variety of industries. In the end, however, UPS considered MUSE "too complex" for their needs, and unable to solve any problem they couldn't otherwise tackle.

Honda of America

Honda of America Manufacturing operates four assembly plants in central Ohio, two of which contain highly automated equipment to help produce roughly 600,000 Accords, Civics, and other models each year. A discussion with Sadie Hodge of Honda's public communications team has given us a peek into these amazing facilities.

Figure 21: Honda's East Liberty Plant

AGVs (or "Automated Guided Vehicles") and a monorail system carry parts from delivery docks to the people or machines that need them. The assembly platforms raise and lower for each associate. Robots install engines, tires, and glass. Robotic welding equipment, designed and engineered by Honda Engineering, completes over 4,000 welds on each vehicle. We're quite interested in discovering how Honda monitors the health & wellness of all this machinery to keep the factory humming.

In addition to automating the assembly process, Honda operates on a "just in time" inventory. This means that at any one time the plant only has enough parts to build cars for a few hours, thereby saving cost. To accomplish this, Honda must closely monitor the entire factory status, and if things are behind schedule, notify suppliers to hold deliveries until things are caught up. Because of the short lead times and massive volume, we'd like to learn what software helps Honda "visualize" this inventory.

Analysis

This section presents a topical breakdown of what we observed and what we learned from the case studies above. In many cases, we have learned about new ideas and new approaches to a particular issue that we have in common with a given industry. In other cases, we found that our approach to an issue has been quite similar to another group's approach. In other cases still, we found that while our approaches were different, this was more because of differences between our field and theirs.

Graphical Presentation

The Montgomery County Traffic Operations tools overlay data on live video and scanned paper maps. While the latter became a maintenance burden, both provide a compelling mix of media types to integrate information and capitalize on the familiar.

The ARTCC TSD combines several effective methods of graphical presentation:

- the map overview shows spatial relationships among aircraft;
- a small area of the screen presents details on the selected aircraft; and
- a detailed spreadsheet-like window appears when an aircraft is double-clicked.

While AVATAR software excels in providing overview information and visualizing detailed telemetry points, it does not provide a robust framework to retrieve or display spacecraft or mnemonic metadata. We can imagine that a small detail area on the screen, or perhaps a tool-tip, could provide information about a given spacecraft (name, health, visibility, time-to-visible, or time-to-invisible, etc.). While this informational pop-up detail may be useful, our software does not currently have mechanisms to access the necessary information.

Network monitoring tools utilize several common techniques of graphical presentation including hierarchical views, maps, and event logs. However, Tivoli's scrollable legends suggest an interesting approach to hierarchy navigation. Imagine a Data Abacus or Bullseye visualization showing the top-10 problematic satellites. Now imagine a scrollable legend alongside it (like the one in Figure 13) in which the colored boxes on the left show the red-yellow-green status of each element in the hierarchy. If the user double-clicks on an entry, the abacus would drill-down to the next level of hierarchy, and the scrollable legend would update with the elements now displayed in the abacus. A right-click could traverse back up the hierarchy, or perhaps post a menu with several options. In theory, the scrollable legend could operate with any visualization that supports hierarchical drill-down.

The Rivet Project's approach to drill-down is noteworthy. Each of the three rows of histograms in Figure 15 shows an additional level of detail, but unlike many drill-down schemes, all levels of detail are displayed simultaneously. Another innovation can be seen in the multivariable histogram at the top of the display. With careful color selection and proper scaling, this visualization simultaneously correlates four variables while showing trends in each. And finally, the yellow manipulator to scroll through historical data is reminiscent of scrolling through cached history of a VisAGE visualization. It would be interesting to know if the manipulator can be resized like in VisAGE to expand or contract the range of the viewport.

The TowerView CyberGrid offers a striking graphical presentation of large quantities of data[11]. Of particular note is that the CyberGrid does not suffer from the occlusion problem that plagues many comparable three-dimensional data visualizations. Because in general there are few dramatic anomalies, the majority of the towers will be quite short (or simply two-dimensional). Therefore, in most orientations of the 3-D space, the anomalies will still stand out, without hiding other anomalies behind it[12]. On another matter, Figure 17 shows a good marriage of 3-D visualization, pop-up details, and additional conventional windows.

NeoVision's Heatmaps remind one of the Grid visualization; the main difference is that Heatmaps show a red-blue gradient, suitable for financial data, whereas the Grid typically shows red-yellow-green health indicators. We could learn, however, from their mechanisms to obtain detail, namely, the right-click to post a menu of options (Figure 19), and a single click (or perhaps even mouse-over) to post a detail pane (Figure 20).

Managing Complexity Issues

Montgomery County's new ATMS prototype allows the operator to hide details they're uninterested in, and zoom in on a geographical area to focus on a particular problem. To make more information visible to the operator without overwhelming them, a two-monitor display is used.

The Metrorail OCC employs several different methods to manage complexity. The principal method is to break down the system into logical groups, that is, by metro line. Any monitoring or analysis is restricted

[11] HighTower Software won an eMillennium Award for Excellence in Technology Implementation for its TowerView software at COMDEX 2000 in the Business-to-Business - Small Organization category in June, 2000.

[12] The narrowness of the towers also contributes to avoiding the occlusion problem.

to the particular rail line selected after login, cutting the amount of data essentially in thirds. We can learn from this approach in the design of CVS by allowing operators to define logical groupings of satellites to focus the scope of a particular operator's CVS session. A group could be a subset of satellites in a constellation, or perhaps the entire power subsystems across all satellites.

The OCC also deals with complexity by grouping different types of data into different screens (views) and by purchasing over 100 CRTs to display different sections of the metro system. While the former approach is a logical, time-honored approach to grouping data, the latter is generally not a practical or preferred approach in mission operations.

The ARTCC TSD (see Figure 6 and Figure 7) shows a controller much more information than he or she can actually comprehend at any given time. Filtering and coloring of data are its most effective techniques to keep the display manageable and readable. With filtering, the tool shows only the aircraft for which the controller is responsible. This is analogous to how Metrorail operations only show a given line of the system on any one display at a time, filtering out areas that are out of the scope of a particular operator's attention. Again, this ability to break down the system into smaller subsets can diminish the perceived complexity of the system.

The TowerView software advocates visual data monitoring to manage complexity. It is an innovative solution that applies well to satellite constellation management. However, there's no reason to conclude that a model of constellation health with suitable visualizations is any less viable of a solution to the same problem domain.

The Rivet Project's tools display thousands of points on-screen, but the end-user need only comprehend the resulting color-coded activity patterns. This powerful technique to display overview information has also been used in computerized galactic cartography and the cancer atlas.

Alert Notification and Propagation

As one would expect, the software we investigated signals error conditions in the system with a variety of graphical effects, such as a flashing icon or a change in color. Many systems supplemented graphical indicators with an event log of some kind (see Figure 4 and Figure 10). In some cases, the event log is always displayed and available (Metrorail OCC and Montgomery County ATMS), in other cases it's an optional screen (or file) only accessed to view historical events. Moreover, some systems include a mechanism to acknowledge alarms, clearing them from the screen. Alerts that remain unacknowledged remain red, or flashing, or perhaps are elevated in severity if the problem persists. We can learn from the importance of event logs in real-time monitoring software, as it remains a valuable supplement to graphical indicators. In fact, in the current version of the ATMS software, operators concerned with traffic control hardware would tend to limit their investigation to the real-time event monitor. Given their expert status, no fancy GUI can provide them more information than can a simple event monitor with detailed status bits and failure codes. We have observed this inclination to character-based screens in our own experience.

All 20 ARTCC computer systems are linked to each other, allowing an operator to view information from any other sector, including its alerts. In general, a controller is only concerned with aircraft in his or her assigned sector. The ARTCC Traffic Control Manager, however, is concerned with how aircraft move through the entire ARTCC airspace. Sector Alerts that a controller sees will also be visible on the TCM's console. This way the TCM can route aircraft around a given sector if the traffic there is too heavy.

Color, Sound and Multimedia

AVATAR team members and their advisors have speculated that nominal conditions should perhaps be represented in white (uncolored) instead of in green as they are now. While the visualizations would appear less striking and colorful, this change would seem to address red-green color deficiency in prospective users. It is perhaps not a coincidence that the TowerView CyberGrid shows nominal conditions in white or gray, not green. In fact, TowerView now ships with an alternate color scheme for red-blind and green-blind “dichromats”[13]. Notice as well that in the ATMS traffic volume status display (Figure 3) the unexpected traffic volume is indicated in *blue*, not red. This could also be the result of color deficiency awareness.

The ARTCC TSD makes effective use of color. Coloring aircraft according to their direction of travel or destination helps the controller keep aircraft in appropriate flight lanes. Automatic coloring of regions on the display show aircraft at an unsafe distance from one another, drawing the controller's attention and helping identify all participants involved in an alert. Moreover, the TSD allows the controller to assign meaning to colors (climbing, descending, traveling north, etc.) that apply to TSD display icons. In CVS, the red-yellow-green colors to indicate health status are not configurable by the end user. However, given the intuitive nature of red-yellow-green health, we’re not convinced that the ability to assign colors would

[13] The HighTower web site contains an entire section on color deficiency with screenshots that simulate how color deficient individuals see the standard and alternate TowerView color schemes. It also contains the standard Ishihara Test for Color Blindness.

be beneficial[14]. However, if later the software supported additional indicators besides health status, such configuration might become worthwhile.

The only use of sound and other media we saw was the audio annunciator in Metro ROCS software and the aforementioned data overlay on live video utilized by the traffic operations facility. In the ARTCCs, the most important use of sound is the controller's radio. At the Coors packaging facility, sound output is not an option due to ambient noise characteristic of any manufacturing plant[15]. It appears, then, that these types of media remain rare in real-time monitoring systems.

System Integration

From several points of view, a key feature of the ATMS prototype in Montgomery County is its ability to bring disparate systems into one desktop. It makes an operator more productive by giving them a single place to look for the information they need, and more effective because data that was previously displayed across the room (and hence ignored) is more likely to be used. The prototype also reduces cost and simplifies training by sharing a common toolset, maps, and display elements, while allowing for the integration of future systems into the same environment. Lastly, and probably most significantly, it lets the operator customize their environment, selecting the tools and data they need to get the job done.

The Metrorail ROCS software is a highly integrated system. All OCC staff use the same system, whether they are line control supervisors, maintenance specialists, or communications center staff. Consequently, they all speak the same "language" and have a common basis of understanding of the monitoring of the system.

Project Dynamics

As learned at Montgomery County Traffic Operations, if a team hasn't had the time to configure a tool to give them useful information, that tool will go unused. Of course, there must be a reasonable assurance that the time invested will pay off in the end. There is a fine balance, then, between making a system configurable enough to be powerful, yet simple enough that it gets used in the first place.

In Montgomery County, It was great to see that the new ATMS prototype was running in the control room, right alongside the traffic team's regular tools. Design meetings and discussions are held there,

[14] Except perhaps to provide alternative color schemes for people with color deficiencies.

[15] In fact, some of the employees who work at the packaging lines are deaf.

making it easy for the team to participate and, we presume, simple to compare and contrast the new system to their existing ones. This immersion, we believe, will allow the tool to mature quite nicely.

Several industries we studied utilize formal methodologies to respond to error conditions typically caused by hardware failures, disasters, or other incidents that require time-critical response. Metro operations uses the Emergency Information System (EIS), which outlines detailed procedures for responding to a variety of types of incidents, including bomb threats, train collisions, and flood. Similarly, Coors Brewing Company follows the "S88 Manufacturing Methodology", a series of procedures for reacting to serious problems during the packaging stage of brewing. And although nothing is in place at present, the traffic engineers foresee the next version of their software suggesting pre-defined courses of action based on earlier similar traffic scenarios. One could imagine that this could evolve into a "methodology" of response to traffic crises.

Conclusions

We have surveyed a variety of industries and products that appeared to address similar problems as multi-spacecraft mission monitoring, particularly in the areas of data visualization and real-time monitoring. Our studies have lead us to visit operations control facilities, to download commercial product demos, to search the World Wide Web, and to contact friends and relatives in targeted industries.

To summarize the most interesting ideas we encountered and the most important lessons we've learned:

- It is important to provide an alternative to default color palettes so that people with color deficiency can select distinguishable colors.
- One approach to simplify a complex data set is to break it down into customizable groups, that is, focus a given operator, screen, or user login to a subset of the totality of the system.
- A scrollable legend could be implemented which traverses through hierarchy, updating both the legend and a visualization with data pertaining to the next level in the hierarchy.
- Event logs and their kin, though less flashy, remain an effective supplement to otherwise graphical user interfaces, especially if they possess color-coded severities and a means to acknowledge alarms.
- With proper scaling and coloring, a multivariate histogram can show at least four variables simultaneously, with visual trends apparent to the end-user.
- A three-dimensional visualization is less likely to suffer from problems of occlusion if the displayed objects are either small, narrow, or both. Visualizations that show spatial relationships, whether in two or three dimensions, remain a powerful technique to depict reality.

- Systems that are integrated with all facets of an operation tend to be the most efficient, valuable, and appreciated by operators.

It is also interesting to note what we didn't encounter. Specifically, nothing we found possessed a plugin architecture of any kind, so common in Code 580 applications, with the possible exception of NeoVision Heatmaps. In addition, there was very little 3D visualization to be found, with the notable exception of TowerView[16]. Nothing operated in a lights-out environment, although network monitoring software supported notification of off-site administrators. Finally, we saw nothing comparable to zoomable user interfaces. Imagine the Traffic Situation Display (Figure 6) with a zoomable front-end. Perhaps further research will reveal other control centers or commercial software that show some of these characteristics.

Further Directions

Our long-term plan is to update this report in each of the next two years. The following list outlines some possible areas for further investigation, based either on our current research, or simply on other industries or areas that we have not yet investigated.

- Due to the proximity of other government organizations such as the NRL, NOAA, and NIH, coupled with the placement of some of our Commerce One colleagues at these facilities, it may be fruitful to investigate the monitoring and visualization capabilities of these establishments.
- Although things haven't moved fast enough for us to speak with Honda in more depth at this time, we believe it will be very valuable to continue discussions with them. If appropriate, we would eventually like to visit their facilities for a first-hand tour.
- Ken Waller of the Metrorail OCC notes that they are "in the process of deciding on the form, fit, and function of a new system," currently referred to as ATS, Advanced Train System. We will no doubt want to check in with them next year to find out the status of this new system.
- Figure 5 shows a prototype of the next version of the Montgomery County ATMS software. We will no doubt want to check in with them as well to find out the status of their new system.
- A table on the Denver Center web page indicated that the ARTCC TSD, when fully implemented, would display geographical information, aircraft information, alerts, airport arrival/departure details, and weather features. With the knowledge that the ETMS is to be deployed in five phases, one could surmise that the last two items in that list represent the last two phases of the ETMS. The state of the ETMS should be addressed in the update to this industry study.

[16] If we had researched applications in the medical industry, we likely would have encountered three-dimensional visualizations.

- The Advanced Traffic Management System (ATMS[17]) is an ongoing research and development program with the goal of applying new technologies to air traffic management problems. All of the tools in the ETMS were developed by the ATMS program and have been phased into the ARTCCs. The ATMS project will continue into the future, and any new developments proceeding from this program should be documented in an update to this industry study.
- We learned from UPS that real-time monitoring doesn't pay-off in their industry as much as others. Their insight into MUSE, however, suggests we ought to take a closer look at how others are using this package to solve their problems.
- The medical industry was untapped and remains ripe for future investigation.
- Joe Hageman at Coors works at their Golden, CO facility, which is one of the older breweries in the United States. Mr. Hageman referred to "more modern facilities" and some of their capabilities. In further updates, we could research more modern manufacturing facilities, be they breweries or other manufacturers. It appears likely that the manufacturing industry would be rife with innovations in real-time monitoring and data visualization, a statement supported by the promise evident in the Honda manufacturing facility.
- Due to our team's recent collaboration with the University of Maryland Human Computer Interaction Lab, we may be able to obtain pointers to additional interesting visualization work performed either there or by their associates.

We believe that all of these areas warrant further research in future updates of this report. By then, perhaps we will have already applied some ideas from this year's findings to AVATAR software, and even more, perhaps we'll have new questions to ask and new topics to consider.

Bibliography and Acknowledgements

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- Sadie Hodge, Communications, Honda of America;
- Jack Brown, Technology Research Project Leader, UPS; and

[17] Be careful not to confuse this ATMS with the Montgomery County Automated Traffic Management System, also ATMS!

- Theron Colvin, Process Design Manager, UPS.

The following World-Wide Web pages were used in this report:

- NeoVision corporate website: http://www.neovision.com/
- Hewlett-Packard: http://www.hp.com/
- Ohio Honda: http://www.ohio.honda.com/
- Intelligent Transportation Society of America: http://www.itsa.org/
- Muse Technologies (now Advanced Visual Systems): http://www.musetech.com/
- Montgomery County Automated Traffic Management System: http://www.dpwt.com/atmspage/
- HighTower Software: http://www.high-tower.com/
- Washington Metropolitan Area Transit Authority: http://wmata.com/
- WhatsUpGold product overview: http://www.ipswitch.com/Products/WhatsUp/index.html
- Stanford University's Rivet project website: http://www-graphics.stanford.edu/projects/rivet/
- Tivoli demo: http://www.tivoli.com/products/demos/tsnm.html
- BMP white paper: "Event Management and Notification":

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